NASA TECHNICAL MEMORANDUM

NASA TM X-52845

NASA TM X-52845

REQUIREMENTS, DESIGN, AND PERFORMANCE OF A CONTROL SYSTEM FOR A BRAYTON POWER SYSTEM

by Ronald L. Thomas, Raymond S. Bilski, and Robert A. Wolf
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
Fifth Intersociety Energy Conversion Engineering Conference
sponsored by the American Institute of Aeronautics and Astronautics
Las Vegas, Nevada, September 21-24, 1970

REQUIREMENTS, DESIGN, AND PERFORMANCE OF A CONTROL SYSTEM FOR A BRAYTON POWER SYSTEM

by Ronald L. Thomas, Raymond S. Bilski, and Robert A. Wolf

Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at

Fifth Intersociety Energy Conversion Engineering Conference
sponsored by the American Institute of Aeronautics and Astronautics
Las Vegas, Nevada, September 21-24, 1970

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

REQUIREMENTS, DESIGN, AND PERFORMANCE OF A CONTROL SYSTEM FOR A BRAYTON POWER SYSTEM

by Ronald L. Thomas, Raymond S. Bilski, and Robert A. Wolf
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

Abstract

The NASA Lewis Research Center is developing a Brayton Space Power System for future manned space missions. This paper discusses the requirements, design, and performance of a Brayton control system. The control system provides the controls and displays required for power system startup, shutdown, and steady-state operation. Also provided is automatic power system protection in the event of engine malfunctions.

The control system is designed for a minimum 5-year continuous operation. To achieve this, special circuits and redundancy have been included in the control system to insure continued safe power system operation even in the event of any single component failure. The control system consists of a signal conditioner connected to a control panel by a transmission cable. The signal conditioner mounts on the power conversion system and the control panel is located in a remote control room.

One of the two systems delivered to NASA has successfully been used to operate a complete Brayton Power System for over 2000 hours including 12 start-stop cycles.

Introduction

The NASA Lewis Research Center is engaged in a program to develop a Brayton power system capable of generating electric power in space. A current version of this power system is designed to deliver 2 to 15 kilowatts of electric output power using a radioisotope as its heat source (Ref. 1). This Brayton power system with a simulated radioisotope heat source is undergoing performance and endurance tests at the Space Power Facility of the NASA Plum Brook Station. Preliminary results of these tests are reported in Ref. 2. All components and subsystems in this power system have as a design objective a 5-year operating life.

The Brayton program at the Lewis Research Center has emphasized the complete system approach. The objective has been to assemble and test a power system complete with all auxiliary subsystems required to operate as a self-contained unit. In this context, a control system was built to operate the power system during testing and at the same time to be evaluated as a subsystem of the power system.

The control system performs the functions of startup, shutdown, power level control, electrical bus protection, malfunction monitoring, and emergency shutdown. It was a goal of the design that all circuits and control concepts were to be directly applicable for future long-term space missions.

The Brayton control system consists of two separate components: a remote control panel and an engine mounted signal conditioner. The remote control panel contains the displays, alarms, manual controls, and automatic controls required to operate the Brayton power system. The signal conditioner operates on all signals passing between the remote control panel and the power system. It conditions all signals to a 0 to 5 volt range. The signal conditioner is mounted on one of the engine cold plates. A hard-wired cable system links the control panel to the signal conditioner.

This paper presents a description of the Brayton power system, the control system requirements, and the design that evolved. Also included are the results of test experience with two delivered control systems and suggested areas of improvement. For a detailed description of the control system the reader is referred to the contractor final design report by AiResearch Manufacturing Company (Ref. 3).

Brayton Power System Description

In order to understand the requirements placed upon the Brayton control system a brief review of the power system is presented. Figure 1 is a schematic diagram of the Brayton power system. A detailed description of the BPS can be found in Ref. 4. The system consists of a gas filled power conversion loop, a liquid filled heat rejection loop, a gas management subsystem and an electrical subsystem. The following paragraphs contain a brief description of each of these subsystems.

Gas Filled Power Conversion Loop

The working fluid of the gas filled power conversion loop is a mixture of helium and xenon gases at the molecular weight of krypton (83.8). This closed gas loop consists of the Brayton Rotating Unit (BRU), heat source heat exchanger, recuperator, waste heat exchanger, and the required gas ducting. The flow path of the gas is indicated in Fig. 1. The BRU consists basically of a radial inflow turbine, a four-pole alternator, and a radial outflow compressor, all of which are mounted on a common shaft. The shaft rotates at 36,000 rpm and is supported on gas-lubricated bearings.

Heat Rejection System

A silicone liquid, Dow-Corning 200, is circulated through three parallel paths to remove heat from the Brayton waste heat exchanger, to cool the alternator, and to cool the system's electrical packages which are mounted on coldplates. This waste heat is rejected to space through a radiator. For added reliability, two identical cooling loops are available, each with its own pump. During normal operation, one loop is active with the other in a passive standby mode.

Gas Management Subsystem

The gas management subsystem supplies gas for BPS startups, for hydrostatic support of the BRU gas bearings, and for gas loop pressure adjustments. It consists of a gas storage bottle, a gas bottle heater, a pressure regulator, nine solenoid valves, and connecting lines to the gas loop. The nine solenoid valves are the injection valve (V-1), makeup valve (V-7), vent valve (V-2), bleed valve (V-3), check valve pilot valve (V-4), and four valves (V-5, V-6, V-8, and V-9) for controlling flow to the gas bearings.

Electrical Subsystem

The electrical subsystem contains all the electrical hardware necessary to operate the BPS. A separate presentation describing the electrical subsystem in detail is given in Ref. 5. This subsystem comprises: (1) the BRU speed control; (2) the alternator voltage regulator; (3) the dc power supply which supplies all BPS dc power requirements; (4) two inverters, one for each liquid pump motor; and (5) the Brayton engine control system (BCS) which provides all of the control logic and conditioning functions required by the BPS and interfaces with all other active components (i.e., valves, relays, instrumentation, and protective devices).

Control System Requirements

Prior to final definition of the Brayton control system design, it was necessary to outline basic system requirements. This section is structured so as to acquaint the reader with the concepts which were used at that time to formulate the design.

General Requirements

The control system for the Brayton Power System (BPS) must be designed in such a manner so as to provide all of the controls, protective logic and displays necessary to operate the system. The control system must be an integral element of the BPS and as such operate directly from BPS dc power. The control system is used during ground tests of the BPS but all control concepts and circuit designs used in the control system must be directly applicable to future long-term space missions.

A major effort must be made to design reliability into the control system. The control system must, as a goal, be capable of operating the BPS continuously for 5 years. The control system must be designed so that a failure of any one part in the control system will not result in loss of BPS output power.

The control system must contain a remote control panel which would be located inside the spacecraft during a space mission. Therefore an attempt must be made to build a compact control panel. Due to facility ground test constraints the control panel must be capable of controlling the BPS from a maximum distance of 400 feet. All signals between the control panel and the BPS must be standardized to 0 to 5 volt range to minimize noise and facilitate the future use of standard telemetry and/or multiplex systems. All control panel displays must be accurate to within ±2 percent of full scale.

Because the control system is to be used during development tests of the BPS, it is necessary to provide displays of additional BPS measurements. These parameters must be displayed on a monitor panel which will be located adjacent to the remote control panel.

Control Functions

In simplest terms, the control system functions are to start up the BPS, to control it during steady-state operations, and to shut it down (Fig. 2). The following paragraphs describe these functions in more detail.

Startup. The startup technique used during the initial phases of the 2 to 15 kWe BPS tests is a gas injection startup. Basically, this starting scheme consists of forcing gas from a high pressure storage bottle through the BRU turbine and overboard through a vent valve. This causes the BRU to spin. When the BRU reaches a self-sustaining speed the injection flow is stopped and the vent valve is closed. The BRU then bootstraps itself up to design speed using the gas which has been trapped in the system at the end of the injection period. After the BRU has reached design speed the gas pressure in the loop is adjusted to its desired value depending upon the desired power level of the BPS.

The startup procedure outlined above consists of nine major steps which must be performed in a definite sequence. The timing between some of the steps is very critical. Failure to follow the proper sequence of steps could result in an aborted startup or damage to the BPS.

A start module is included in the control panel whose function is to assist the operator during the crucial startup period. The start module must meet the following requirements: (1) it must bring together in one place all the information the operator needs to start the engine; (2) it must keep track of the engine status and inform the operator of this status; (3) it must prohibit the operator from mistakenly violating the proper sequence of events; and (4) it must perform the most critical startup steps automatically.

Steady-state. During normal steady-state operation the only automatic control required of the control system is that of gas inventory control. This control is to automatically compensate for the rise in gas loop pressure as the engine heats up following startup and to compensate for minor leaks in the gas loop during long-term operation. The operator must be able to set the desired BPS gas pressure level from the control panel.

The only other steady-state controls required by the BPS are regulation of BRU speed and regulation of alternator output voltage. These controls are contained in the electrical control package of the electrical subsystem.

In addition, the control system must provide the operator with manual controls for all BPS control devices and furnish him with the status of the BPS at all times.

Shutdown. The BPS shutdown procedure consists primarily of turning off the heat source, providing hydrostatic gas for the BRU bearings, and applying an electrical load to the BRU alternator. This causes the BRU to decelerate down to zero speed. The entire procedure consists of seven major steps. As was the case with the BPS startup, these steps must be performed in a definite sequence. A module, identical in concept to the startup module, is required to assist the operator during shutdown.

Protection Considerations

The control system must protect the BPS and its surrounding environment during BPS malfunctions, but shall permit continued power system operation if at all possible. Automatic control action is to be utilized when very quick corrective or protective action is required (Fig. 3). For example, should the BRU begin to overspeed, corrective action must be taken immediately (within 1 sec). If this corrective action fails, the BPS must immediately be shut down (within a few seconds). In this case automatic action is manditory.

Automatic protective circuitry must be included for the following conditions: (1) BRU overspeed and underspeed; (2) gas loop overpressure and underpressure; (3) bearing cavity underpressure; (4) gas loop overtemperature; (5) alternator overvoltage and undervoltage; and (5) alternator overcurrent. All control actions shall be accompanied by alarms which tell the operator what has occurred. Provision must be made so that all of the protective circuits can be overriden manually by the operator from the control panel.

In order to insure long-term uniterrupted BPS operation, the control system must contain self-checking circuitry. In cases of failures of the automatic circuitry, the self-checking circuitry must inhibit the automatic action and notify the operator of the failure by means of an alarm. The operator must, where possible, be able to replace or repair the failed circuit without causing a BPS shutdown.

Control System Design

A control system which meets all the requirements for controlling the BPS has been designed and built. This control system consists of a signal conditioner connected to a control panel by a transmission cable (Fig. 4). The signal conditioner is mounted on a BPS cold plate and the control panel is located in a remote control room. The control system design is discussed in the following sections.

Reliability

To meet the reliability requirements the following guidelines were utilized in designing the control system circuits: only solid state devices and integrated circuits were used; all circuit components were sized to operate in derated modes; and a detailed thermal analysis was performed on the signal conditioner design to insure that all components operate within their temperature specifications.

A failure mode analysis was conducted to determine the level of redundancy and preferred failure modes for each BPS control device. In those cases where control devices were used only as a backup, no redundancy was provided. Other devices having preferred failure modes were provided with either series or parallel redundancy. For very critical control devices both series and parallel redundancy were provided; this permits normal operation of the device even if a component failure were to occur.

After each control circuit was designed, a failure mode effects analysis was conducted on it. Every component was examined to determine if its failure could result in loss of BPS power output. If such a failure could occur the circuit was redesigned.

Signal Conditioner

A signal conditioner package was designed to meet the requirement that all signals between the BPS and the control panel must be 0 to 5 volts. This package is mounted on a fluid-cooled heat sink (cold plate) on the BPS frame (Fig. 5) and is designed to meet the environmental specifications of the BPS (Ref. 6).

The signal conditioner provides conditioning for all the BPS signals to the control and the monitor panels. These signals are:

33 temperature measurements; 13 pressure measurements; 6 flow rate measurements; and 23 electrical measurements. The signal conditioner also conditions all command signals from the control panel to the BPS.

Besides conditioning signals to and from the BPS, the signal conditioner serves as a junction box. All dc power leads, commons, and direct wired valve and relay position indicators are wired through the signal conditioner. The signal conditioner operates directly from BPS ± 28 volt dc power and requires approximately 140 watts of continuous power.

Mechanical Design. The signal conditioner is a welded aluminum chassis 8- by 14- by 25 inches weighing 80 pounds and is shown in Fig. 6. The chassis has provision for 21 printed circuit cards 5- by 10 inches, although only 19 cards are used. A typical P.C. card is shown in Fig. 7. Metal heat sinking frames are provided on these cards to aid in conducting internal heat from the components to the coldplate. Provision has also been made to cover these boards with a potting compound to aid in removing heat.

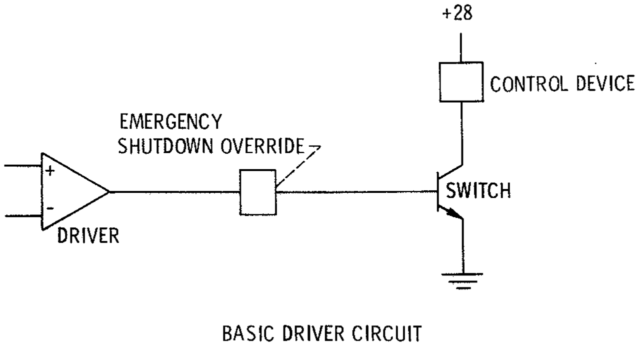
Connectors are provided at each end of the chassis. Sixteen connectors on one end interface with the engine and 11 on the other end interface with the control panel. Two additional connectors on the control panel side are used for test points. By making measurements at these two connectors it is possible to check all redundancy in the signal conditioner without opening the package.

Circuits. Twelve types of circuits were developed to meet the signal conditioner requirements. These circuits fall into the two major classifications of sensing circuits and control circuits.

For the thermocouple inputs it was necessary to provide a reference temperature. Thermistor controlled ovens were developed for this purpose. These ovens within the signal conditioner maintain a reference temperature of $100^{o}\pm0.5^{o}$ C.

The signal conditioner also contains triply redundant emergency shutdown circuits. These are the only circuits with logic control functions in the signal conditioner. These circuits are actuated by a 115 percent BRU overspeed signal or by a manually operated switch on the control panel. All circuits for control devices used during an emergency shutdown contain special override logic. The outputs of the emergency shutdown circuits tie into this override logic to operate the valves, relays, etc. Two out of three of the emergency shutdown circuits must agree before an emergency shutdown is initiated. The emergency shutdown takes precedent over all other signals, i.e., valves, relays, etc. cannot be controlled from the control panel during an emergency shutdown.

Redundancy. To achieve reliable control system operation, several forms of redundancy are designed into the signal conditioner. First, the input receiver amplifier for every driver circuit is of a differential type; that is, two signals must be available to operate the driver.



BASIC DRIVER CIRCUIT

For example, when the control device is off (normal operation) the minus input is high and the plus input is low. Before the driver can be turned on, the plus lead must be high and the minus must be low. Two highs or two lows result in the driver turning the control device off (normal condition) thus preventing a single failure from causing a driver to operate.

When preferred failure modes are clearly dictated, dual redundant circuits are used. Depending on the preferred failure mode, the dual drivers are operated in series or parallel. For critical circuits, triple redundant drivers are used. The triple redundant drivers provide normal operation even in the event of a driver failure. These triple redundant drivers are used for operating the critical jacking gas valves and the gas loop vent valve.

The redundancy discussed above is carried back through the power supplies. These are three +10 volt dc, three -10 volt dc, and three +5 volt dc power supplies in the signal conditioner. These supplies operate from BPS ±28 volt dc power. If a +10 volt power supply should fail, for example, all triply redundant control circuits would still operate and all dual redundant circuits connected to that power supply would fail in the preferred mode.

Transmission System

It was decided that the simplest and most reliable interface between the control panel and signal conditioner for ground development tests would be a direct wired cable system. This cable system consists of 11 cables with a total of 314 conductors. The weight of this cable is approximately 4.8 pounds per foot. This cable system is designed to meet the environmental specification of the BPS (Ref. 6).

Control and Monitor Panels

The control panel provides the operator with the BPS status, automatic protection and control, and manual controls. The monitor panel provides displays and alarms for BPS parameters that are not displayed on the control panel. The control and monitor panels are contained in one console (Fig. 8). This console contains a card file with 77 printed circuit cards for all the electronic components, and a calibrator-testor for adjusting and checking all circuits on these cards. An example of these printed circuit cards is shown in Fig. 9. Four designs make up 47 of the 77 printed circuit cards in the control panel. The control panel circuits are supplied by primary and backup ±15 and +5 volt dc power supplies. These power supplies operate from BPS ±28 volt dc power. The control panel requires approximately 130 watts of BPS ±28 volt dc power.

The control panel circuits were designed for ease of replacement and interchangeability. Because the control panel might be located in a spacecraft, its circuits will be accessible. The ability to replace failed circuits increases the probability of success for a long-term space mission.

Control Panel Modules. The control panel consists of 11 compact modules. Each module contains automatic logic, manual override switches, meters, position indicating flags, and alarm lights. These panels also display appropriate subsystem graphics to aid the operator in the BPS operation.

Start Module. The start module shown in Fig. 10 provides the operator with a safe sequence for starting the BPS. When the operator has correctly completed a prestart check list he can initiate the power system startup. The control system automatically controls the necessary control devices to start the BPS. During startup the operator is informed of all control actions and valve positions by means of indicating flags on the start panel. A final flag confirms that startup is complete after the operator has completed his checklist.

Stop Module. The stop module (Fig. 10) provides the operator with a safe procedure for shutting the BPS down. This procedure consists of: placing all control panel switches in the correct position; cooling the heat source down; applying hydrostatic gas; and applying parasitic load to the alternator. After the BRU has been safely shutdown the stop module provides indication to inform the operator that he has completed his check list correctly.

Liquid Loop Module. The liquid loop module (Fig. 11) provides the operator with manual control of each pump. Alarms and readouts for each of the liquid loop flows and hot-spot temperatures are also provided.

Gas Inventory Module. The gas inventory module (Fig. 11) provides automatic control and protection for the BPS gas loop. The automatic control consists of pressure level control. The operator can select a pressure setpoint on the gas inventory module panel for compressor discharge pressure. Automatic control logic then operates a small makeup valve and a small bleed valve to control gas loop pressure within ±0.5 psia of the setpoint. Indicating flags on the panel inform the operator when a valve is open and which valve it is. A continuous operation alarm informs the operator when either of the valves is opened for longer than 60 seconds indicating a possible leak in the gas loop.

This module also provides protection for the BPS if the gas loop pressure exceeds 62 psia. If a large gas leak develops from the gas management subsystem into the gas loop, pressure switches sense the overpressure. These pressure switch closures cause the control logic to operate the vent valve to keep the BPS pressure at a safe level.

Critical Parameters Module. The purpose of the critical parameters module (Fig. 12) is to give the operator a snapshot view of the BPS status. A five-digit display is provided for BRU speed. Three dual scale meters are provided for key BPS pressures and temperatures. Also provided are alarms for critical temperatures, over and under speeds, and control panel power supply malfunctions.

Emergency Shutdown Module. The emergency shutdown module (Fig. 12) provides the operator with the means for manually shutting the BPS down quickly but safely. This module contains the shutdown switch, flags for indicating to the operator the status of key control devices during a shutdown, and a shutdown alarm.

Gas Bearing Module. This module (GBM) is also shown in Fig. 12. The purpose of this module is to provide protection for the BRU gas bearings during operation. The bearings normally operate hydrodynamically on the gas in the alternator cavity. However, if this pressure gets too low or BRU speed gets too low, these bearings lose their load carrying capability. Under these conditions the bearings can be safely operated if they are pressurized from an external source. The GBM monitors cavity pressure and BRU speed and supplies gas to the bearings automatically whenever speed or pressure is low.

Heat Source Module. The heat source module (HSM) also shown in Fig. 12 interfaces the control system with the electric heat source. The HSM provides BPS protection by shutting off the electric heat source if the compressor inlet temperature gets too high or if there is an emergency shutdown. This module will require modification when the BPS is mated to a radioisotope heat source.

Valve Control Module. The valve module (VM) shown in Fig. 13 provides the operator with: the manual control switches for all the valves; flags for indicating positions of all valves and pressure switches; meters and alarms for gas bottle supply temperature and pressure; and a variable setpoint control for the gas bottle pressure alarm. Also the VM contains a graphic display showing concisely how all the valves, pressure switches, and gas supplies are located in the BPS.

The valve control switches all have close, automatic, and open positions. Since manual operation of these switches disconnects all automatic control connected to a particular valve, each switch must be pushed in before it can be turned. This is to remind the operator that he is removing all automatic control from any valve he operates manually.

Electrical Control ac. The ac electrical control module is shown in Fig. 14. This module provides the operator with all the BPS ac readouts, alarms, and manual controls. This module also provides several automatic control and protection features.

The readout includes the alternator phase voltages, phase currents, power, and field currents. Also displayed is the power supplied the user. Alarms are provided for over and under alternator voltages, high phase currents, and failure of module circuitry. Manual control switches allow the operator to connect or disconnect the user's load from the alternator, flash the alternator field, operate the alternator field from a backup power source, and override the speed control channels full on or full off.

Automatic control removes the user's load from the alternator if the BRU goes under speed or if any phase current exceeds 150 percent of design. Load is added to the alternator if the BRU speed exceeds 105 percent of design. Automatic control is also provided to switch the alternator field to a backup supply if the alternator voltage goes high or low.

Electrical Control dc. The dc electrical module shown in Fig. 15 provides the operator with dc electrical displays, alarms, and overrides. The dc displays include the battery voltages, currents, status and temperatures, and the dc bus voltages and currents. The alarms warn the operator of a high or low dc bus voltage or a low battery voltage.

Manual override is provided for the operator to connect or disconnect the battery from the dc bus. This allows the battery to be disconnected after BPS shutdown to prevent battery leakage and allows reconnection of the battery prior to BPS startup. Manual overrides are also provided for commanding the battery chargers on or off and for supplying power to the gas bottle heater.

Monitor Panel. The monitor panel (Fig. 16) is an auxiliary panel to the control panel for use only during development tests of the power system. The monitor panel provides no automatic control or protection. Its two main functions are: (1) supply the operator with additional readout and alarms not available on the control panel; and (2) provides output buffering of all control panel signals to be used with a digital data acquisition system. All signals used in the monitor panel from the control panel are routed through isolation amplifiers. This prevents monitor panel electrical failures from affecting the signals used for control of the BPS. Since the monitor panel is designed only for development tests and would not be used for a space mission, it does not operate from the BPS ±28 volt power. All monitor panel power comes from the 110 volt ac test facility power system.

Special Circuit Designs. All critical BPS signals are triply redundant from the engine through the signal conditioner to the control panel. To check these triply redundant analog signals an analog selector circuit was developed. The analog select circuit is designed to prevent incorrect control action from being taken on an erroneous analog signal. The analog selector compares the three signals against each other and rejects one if it does not agree with the other two. The amount of allowable error among the three signals is adjustable. The analog selector circuit also issues an alarm signal to the operator to notify him when there is a discrepancy among the triply redundant signals.

The 0 to 5 volt analog signals are required to be accurate to within ±2 percent of full scale. These signals are transmitted from the signal conditioner to the control panel by means of a cable that may be up to 400 feet in length. To prevent voltage drops in the 400-foot ground returns from causing signal errors: a special differential analog receiver circuit is used; and all analog signal returns are referenced at one point in the signal conditioner and at one point in the control panel. A differential analog receiver is then used to correct the analog signals at the control panel for the difference in voltage between these two ground points.

Performance

Two control systems have been built to date. Both of these control systems have gone through extensive acceptance testing. The first system is now being used to control a BPS during development tests. The second system is being evaluated as part of a Brayton electrical subsystem test. This section discusses the acceptance tests performed on the two control systems and the success of the first control system in controlling the BPS.

Acceptance Testing

After assembly of each Brayton control system and prior to shipment to NASA an extensive checkout was conducted. The signal conditioner was operated over a range of temperatures and under vacuum conditions. It was necessary to design and fabricate a load simulator to check all the control system functions. This load simulator is a device which electrically simulates all BPS instrumentation and control devices.

Both control systems successfully completed all parts of the acceptance test. Minor problems occurred during checkout and these problems were corrected as discovered. Two of these problems are worth mentioning. The thermocouple signal conditioners were found to be sensitive to high frequency noise. When not subjected to high frequency noise the circuits meet all required specifications. Methods of modifying these circuits to eliminate noise sensitivity are being evaluated. The thermocouple noise sensitivity became apparent because of a problem in the signal conditioner power supplies. The originally designed switching regulator power supplies were very noisy and were causing excessive noise in the analog signal channels. As a temporary solution low noise, series-regulator power supplies were fabricated by NASA. These supplies are presently being used for BPS development tests. Low noise, high efficiency replacement supplies are presently being built to solve this problem permanently.

Brayton Power System Tests

Following delivery of the control system to the NASA Space Power Facility in Sandusky, Ohio on May 6, 1969, the control system was installed as part of the BPS. The control system again underwent a checkout. This time, the system's interfaces with the rest of the Brayton hardware and the digital data acquisition system was checked. Several minor problems were uncovered and corrected at this time. Having passed these tests, the control system was ready for the first BPS startup. Figure 17 is a summary of the control system performance during BPS testing.

As of this writing, the Brayton control system has logged approximately 3000 hours of operation. This time includes approximately 2000 hours of use controlling the BPS during development tests. The control system has been used for startup and shutdown of the BPS 12 times.

The automatic control and protection circuits have operated successfully a number of times. On one occasion too much vehicle load was applied to the alternator and the BRU speed began to decrease. However, at 90 percent of design speed the control panel logic automatically removed the vehicle load and applied hydrostatic gas to the BRU bearings. This action allowed the BPS to return to design point operation and prevented a BPS shutdown.

The automatic gas pressure regulation provided by the gas inventory module has also been used extensively to control gas loop pressure to within 0.5 psia of the desired value. A small gas leak developed in the electrically simulated isotope heat source. The control system automatically cycled the makeup valve several thousand times during the endurance tests to maintain the desired gas loop pressure.

The BPS parameters displayed on the control panel have enabled the operator to determine the exact status of the BPS at all times. In addition, the control system is the prime source of all electrical system data taken during the development runs.

Two problems have been encountered during BPS operation that have resulted in design efforts to modify control system circuitry. One problem occurred during early startup attempts. During BPS startup, pressure fluctuations in the gas management system caused the pressure switches in the gas bearing supply lines to make and break contact repeatedly. These pressure fluctuations were unanticipated and therefore not accounted for in the startup logic. This disturbance caused the startup logic to "repeat itself" and resulted in an aborted startup. The temporary solution to the problem was to switch the starting logic off immediately after gas injection cutoff. This permitted a proper BPS start. A better solution involves a redesign of the starting logic taking into account the effects of these pressure fluctuations. This has been done and is presently in the checkout stage.

The second problem occurred because of the BRU speed sensing circuits in the signal conditioner. These circuits convert the alternator output frequency into an analog voltage proportional to speed. However, for frequencies above 120 percent of design the circuit outputs fold-back. Figure 18 shows indicated BRU speed from these circuits versus actual BRU speed.

During one of the research runs, a short occurred among all three phases of the Brayton alternator. This resulted in a distorted alternator output voltage waveform which appeared to the inputs of the speed circuits as a large overspeed. Because the shorted alternator effectively had no load, the BRU began to overspeed. The speed sensing circuits, because of the fold-back characteristics, detected no overspeed; in fact, the output of the speed circuit was that of a "low" speed (see Fig. 18). As a result, no overspeed signal (115 percent of design) was available for actuating the emergency shutdown and the BRU being tested at the time was damaged by overspeed. The speed circuits are under investigation so modifications can be made to prevent them from folding back.

Concluding Remarks

This paper has discussed the requirements, design, and performance of a control system for a Brayton power system. Two of these control systems have been built and tested. The first one is being used to control a Brayton power system during development testing, and the second is being evaluated in an electrical subsystem test. The control system consists of an engine mounted signal conditioner, connected to a remote control panel by a transmission line. The signal conditioner meets the power system environment requirements of vacuum, temperature, and radiation. The control panel is designed to operate in a control room environment.

The control system provides power system startup and shutdown logic, automatic control and protection, signal conditioning of all power system transducers, system status, and automatic and manual control of all power system hardware. The control system is designed to provide these functions for 5 years or longer. This is accomplished by using the latest state-of-the-art integrated circuits and providing redundancy of all critical control circuits. A major effort was incorporated in the design to make the control system tolerant to failures; individual components may fail, but no single failure will cause the Brayton power system to be unable to produce usable electric power.

An effort was made to make the control panel modular and to provide interchangeability of circuits. A failed circuit can be replaced without shutting the power system down. The signal conditioner, however, was designed for unattended engine operation and is to operate for 5 years or more without maintenance.

Depending on the mission, the electrical packages on the engine may or may not be accessible. If it is at all possible to provide accessibility to this equipment it should be done. The ability to periodically check all circuits for failures and to replace a failed circuit easily would certainly increase the probability for success of a long-term space mission.

The transmission system connecting the signal conditioner and the control panel consists of 11 cables. For a future system a single wire multiplexer system with hard-wired overrides may provide the required reliability at much less weight. The control panel and signal conditioner interfaces are all 0 to 5 volts to facilitate such a design.

An effort was made to design the control panel compactly. However, now that initial ground development testing of the Brayton power system has been completed, data channels, alarms, and displays which are not absolutely essential to the power system operation could be removed from the control panel. Also, the tested power system startup and shutdown procedures can now be designed to be completely automatic. These changes will result in a more compact, reliable, and lighter weight control panel.

One of these control systems has successfully started the Brayton power system, presently under evaluation, 12 times and has provided all power system control and protection for approximately 2000 hours.

In summary, the control system discussed in this paper has been successful in controlling a Brayton power system. Control concepts and circuits have been developed that are directly applicable for future space power systems.

References

1. Klann, J. L., Vernon, R. W., Fenn, D. B., and Block, H. C.; "Performance of the Electrically Heated 2 to 15 kWe Brayton Power System," To be presented at this conference.

2. Fenn, D. B., Deyo, J. N., Miller, T. J., and Vernon, R. W.; "Experimental Performance of a 2-15 Kilowatt Brayton Power System in the Space Power Facility Using Krypton," TM X-52750, 1970, NASA, Cleveland, Ohio.

3. Staff of Airesearch Mfg. Co., "Brayton Control System for a Brayton Power System," CR-72697, 1970, NASA, Cleveland, Ohio.

4. Brown, W. J., "Brayton-B Power System - A Progress Report," Proceedings of the Fourth Intersociety Energy Conversion Engineering Conference, AIChE, New York, 1969, pp. 652-658.

5. Thollot, P. A., Bainbridge, R. C., and Nestor, J.; "Description and Performance of the Electrical Subsystem for a 2 to 15 kWe Brayton Power System," To be presented at this conference.

6. Anon., "Brayton Cycle Subsystems and Component Environmental Specifications," No. P-1224-1, Jan. 31, 1967, NASA, Cleveland, Ohio.

E-5774

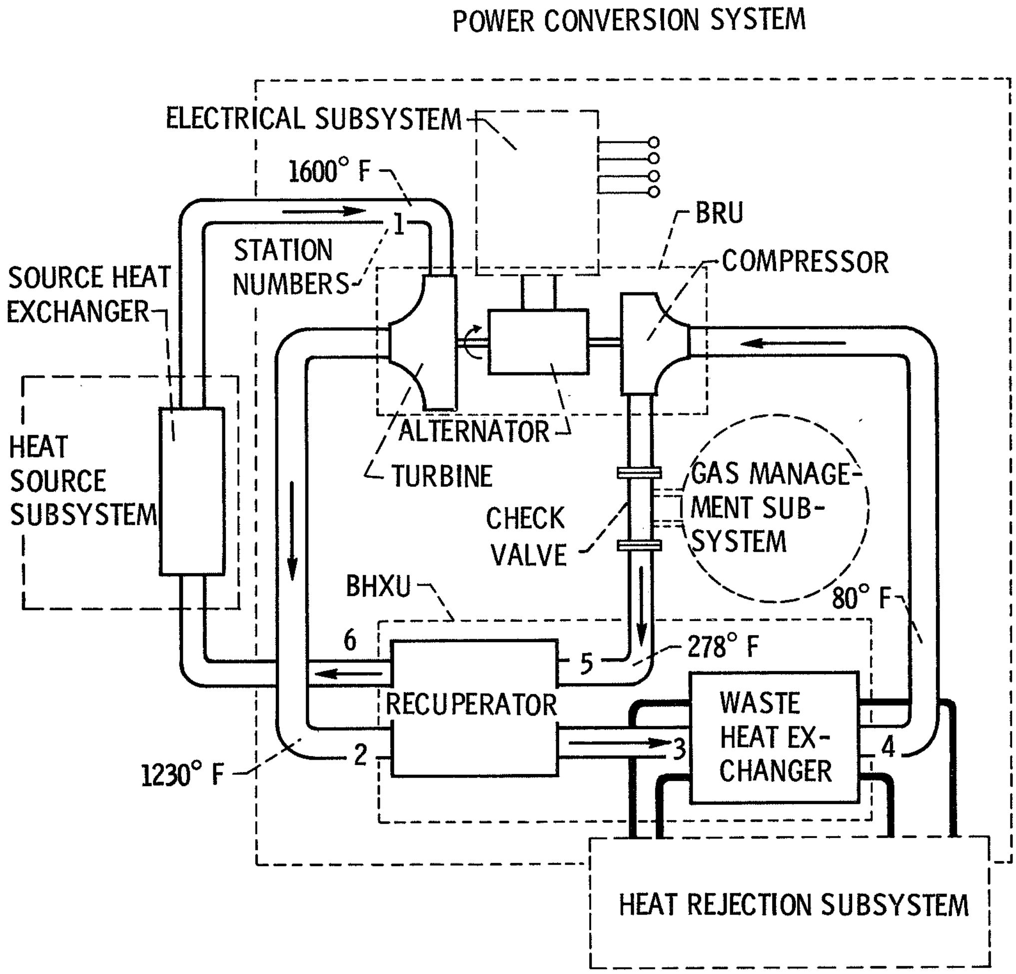


Figure 1. - Schematic diagram, Brayton power system.

CONTROL FUNCTIONS

BPS STARTUP
BPS SHUTDOWN
GAS LOOP PRESSURE LEVEL CONTROL
MANUAL CONTROL OF ALL BPS CONTROL DEVICES
BPS STATUS

Figure 2. - Brayton control system control functions.

E-5774

PROTECTION CONSIDERATIONS

BRU OVERSPEED AND UNDERSPEED
GAS LOOP OVER AND UNDER PRESSURE
BEARING CAVITY UNDER PRESSURE
GAS LOOP OVER TEMPERATURE
ALTERNATOR OVER AND UNDER VOLTAGE
ALTERNATOR OVERCURRENT
ALARMS FOR OUT-OF-TOLERANCE CONDITIONS
ALARMS FOR FAILED CIRCUITRY

Figure 3. - Brayton control system protection functions.

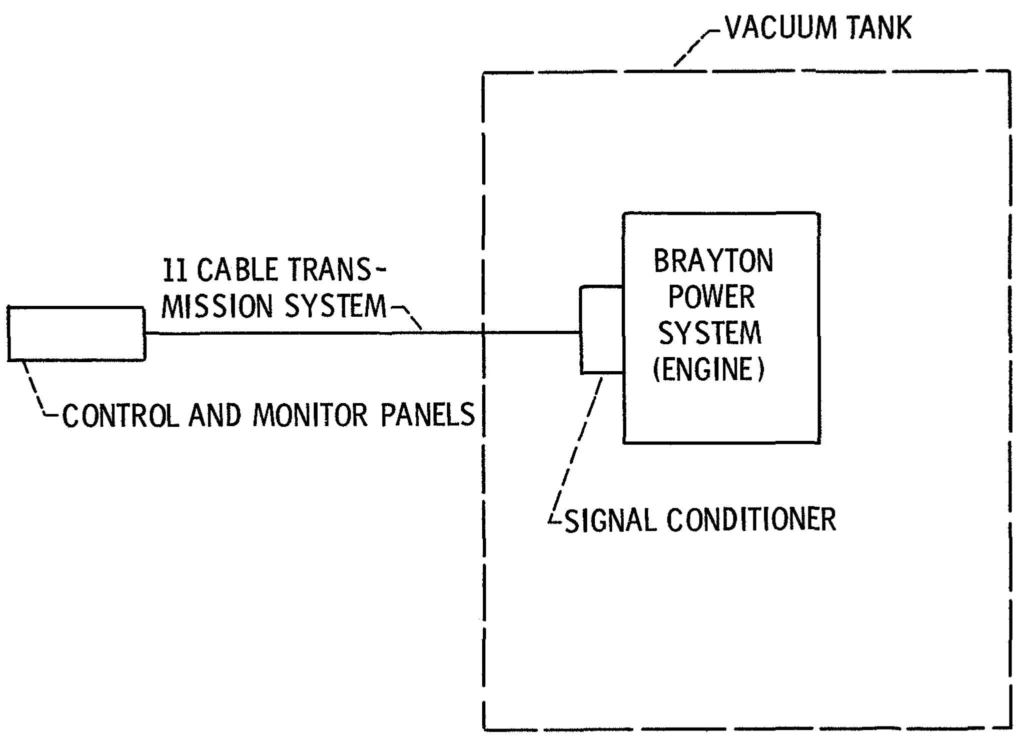


Figure 4. - Brayton control system.

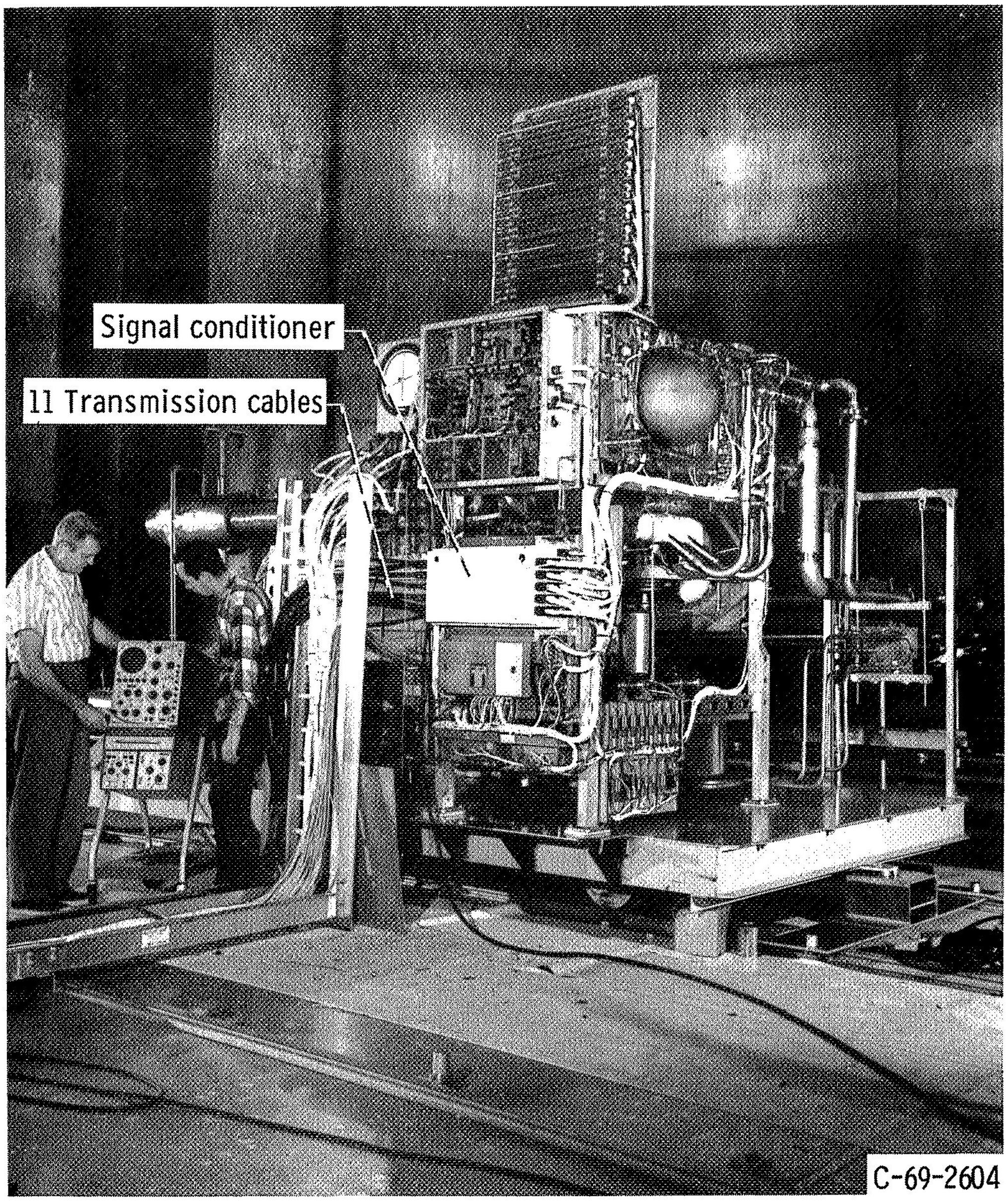


Figure 5. - Brayton Power System showing signal conditioner mounted on cold plate.

E-5774

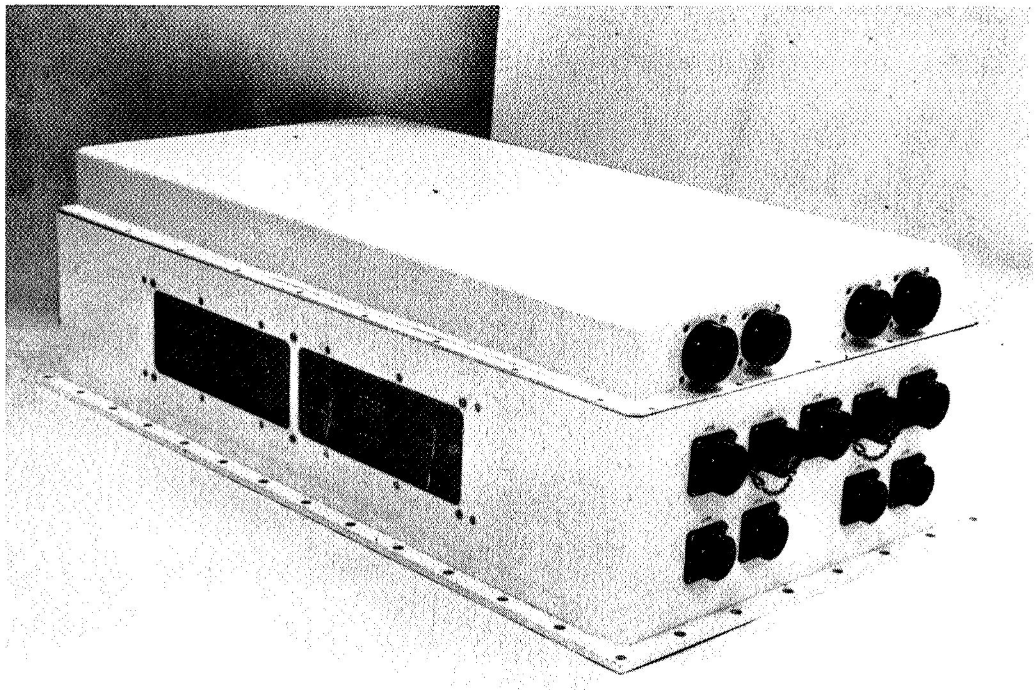


Figure 6. - Signal conditioner.

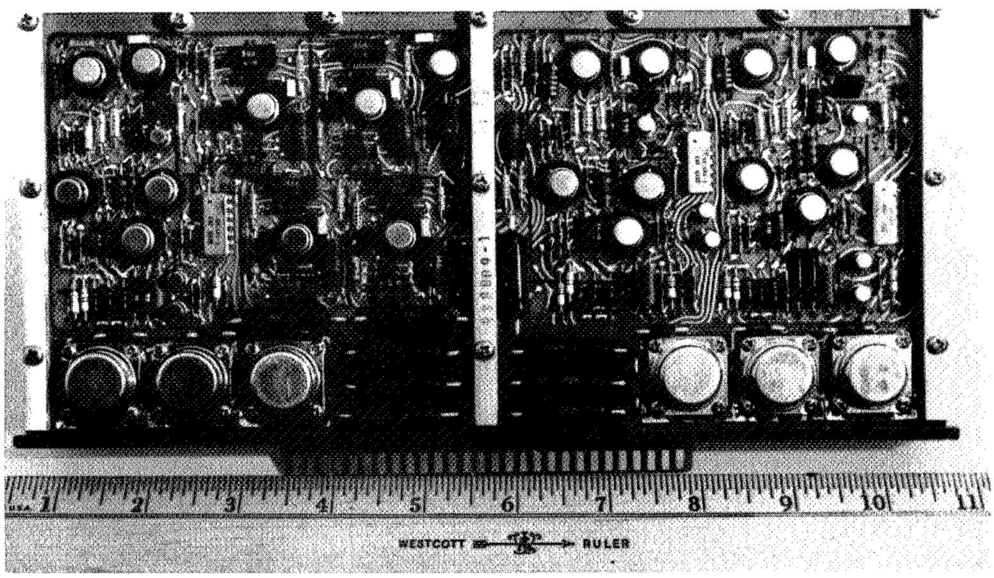


Figure 7. - Typical signal conditioner printed circuit card.

E-5774

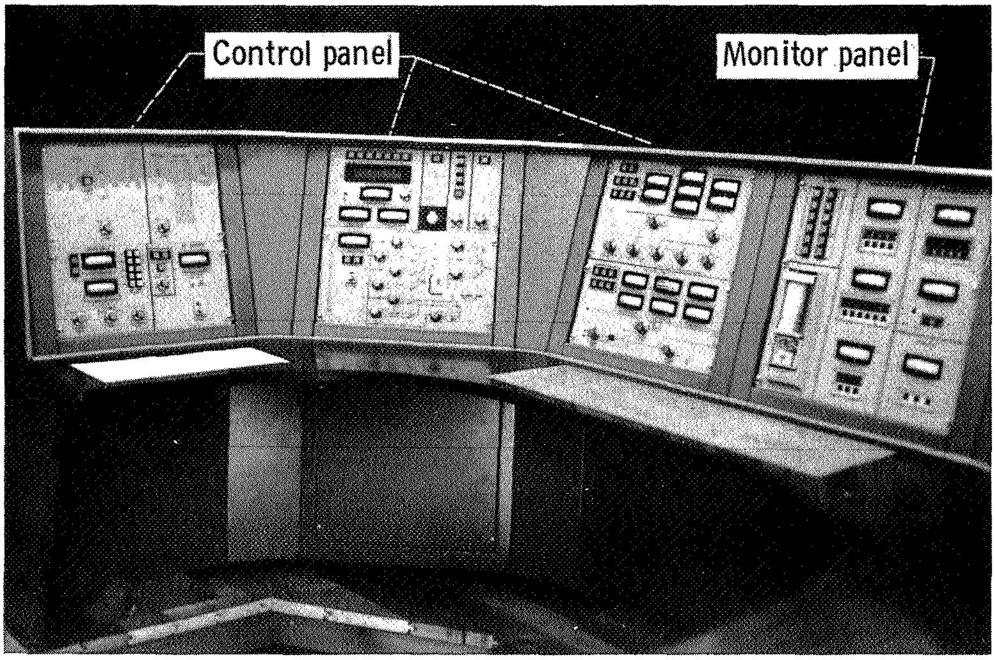


Figure 8. - Control and monitor panels in control system console.

E-5774

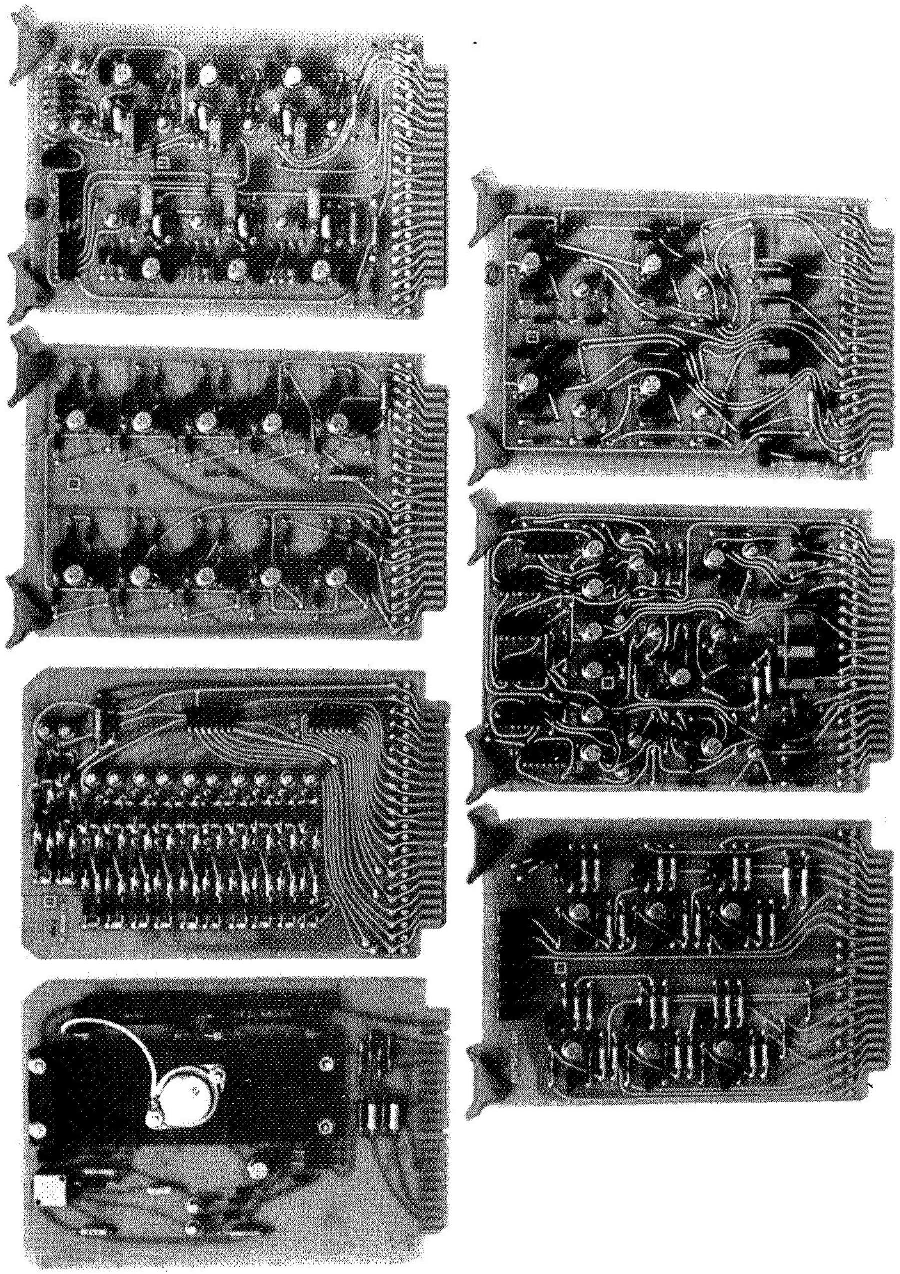


Figure 9. - Control panel printed circuit cards.

E-5774

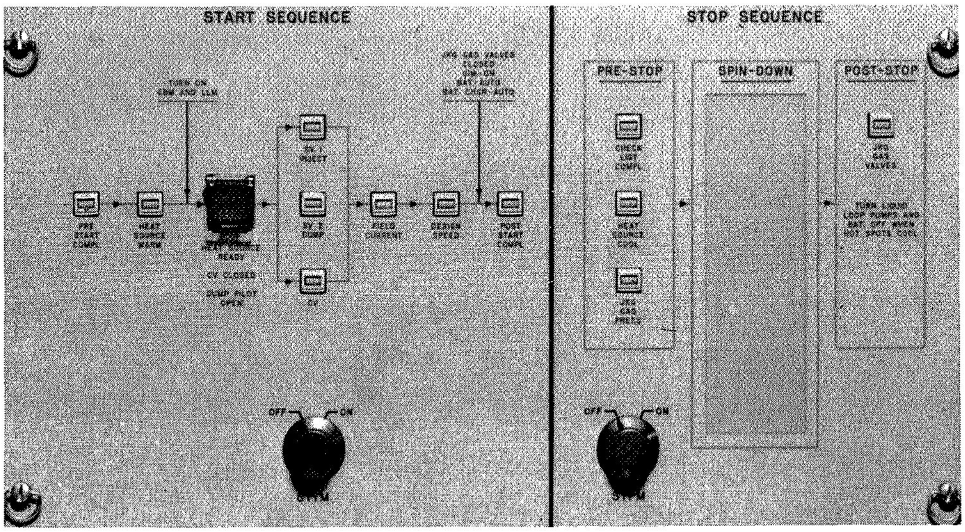


Figure 10. - Start and stop modules.

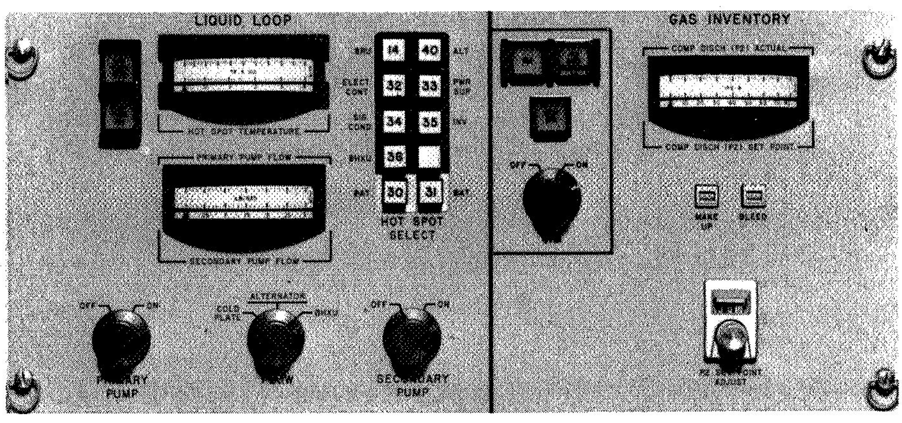


Figure 11. - Liquid loop and gas inventory modules.

E-5774

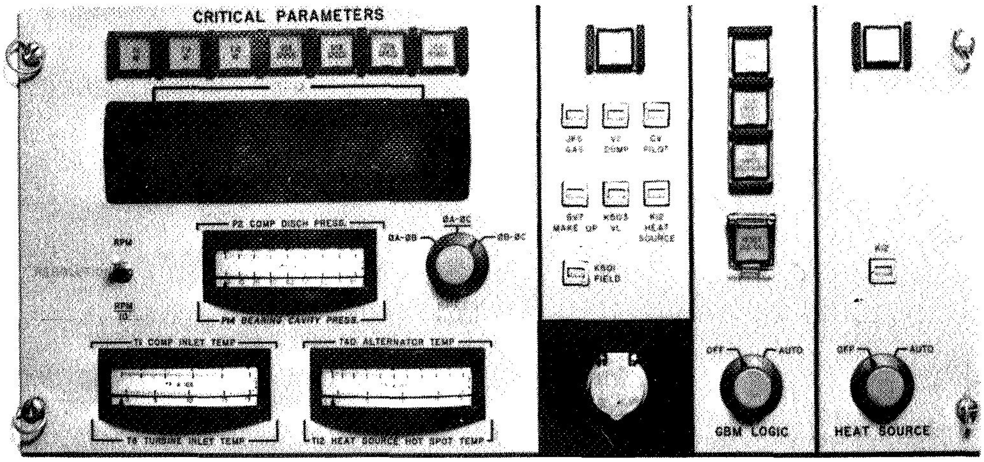


Figure 12. - Critical parameters, emergency shutdown, gas bearing, and heat source modules.

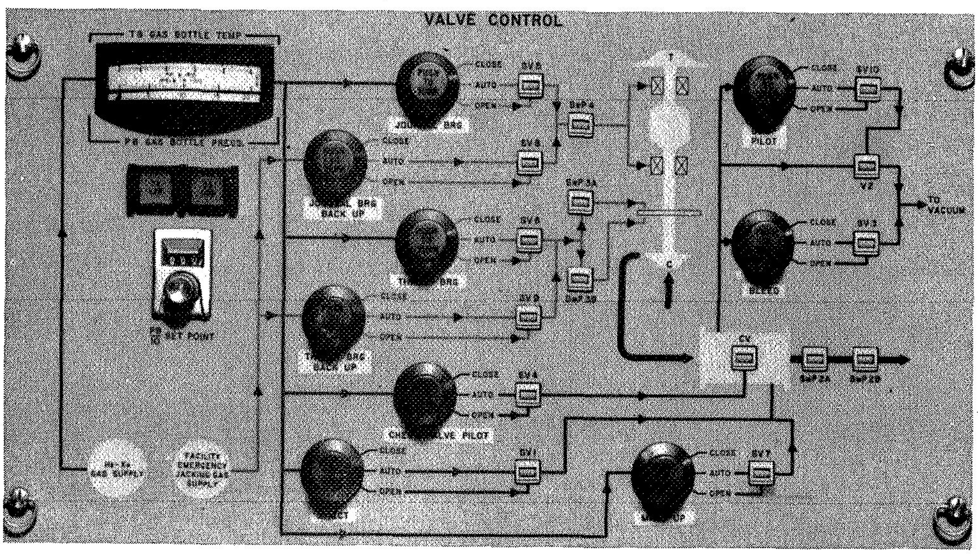


Figure 13. - Value control module.

E-5774

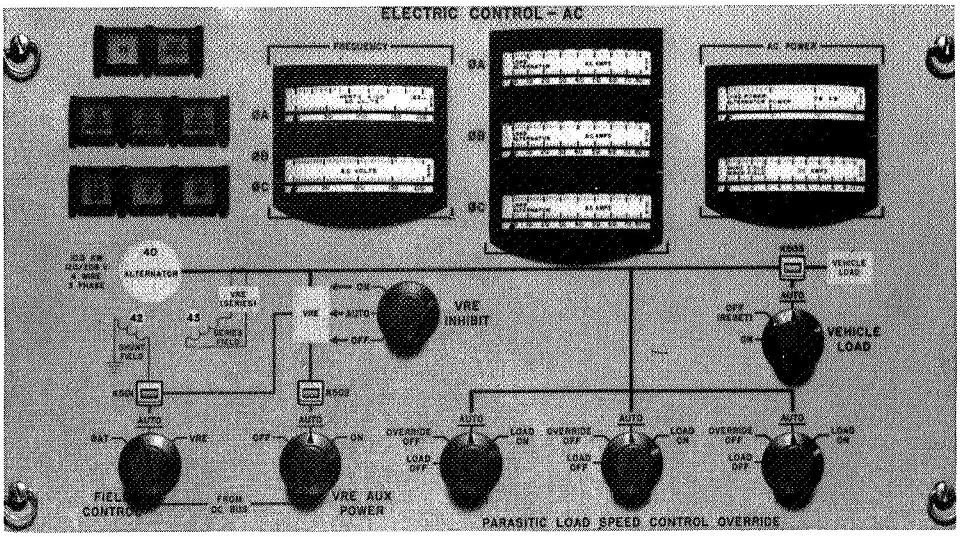


Figure 14. - Electric control module - AC.

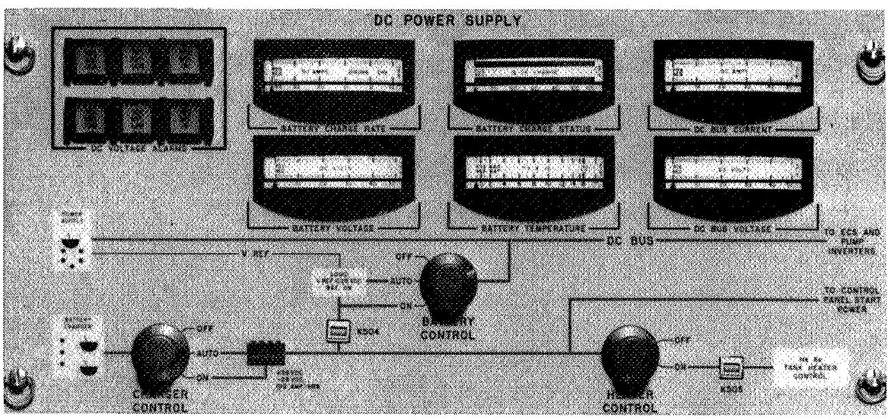


Figure 15. - Electric control module - DC.

E-5774

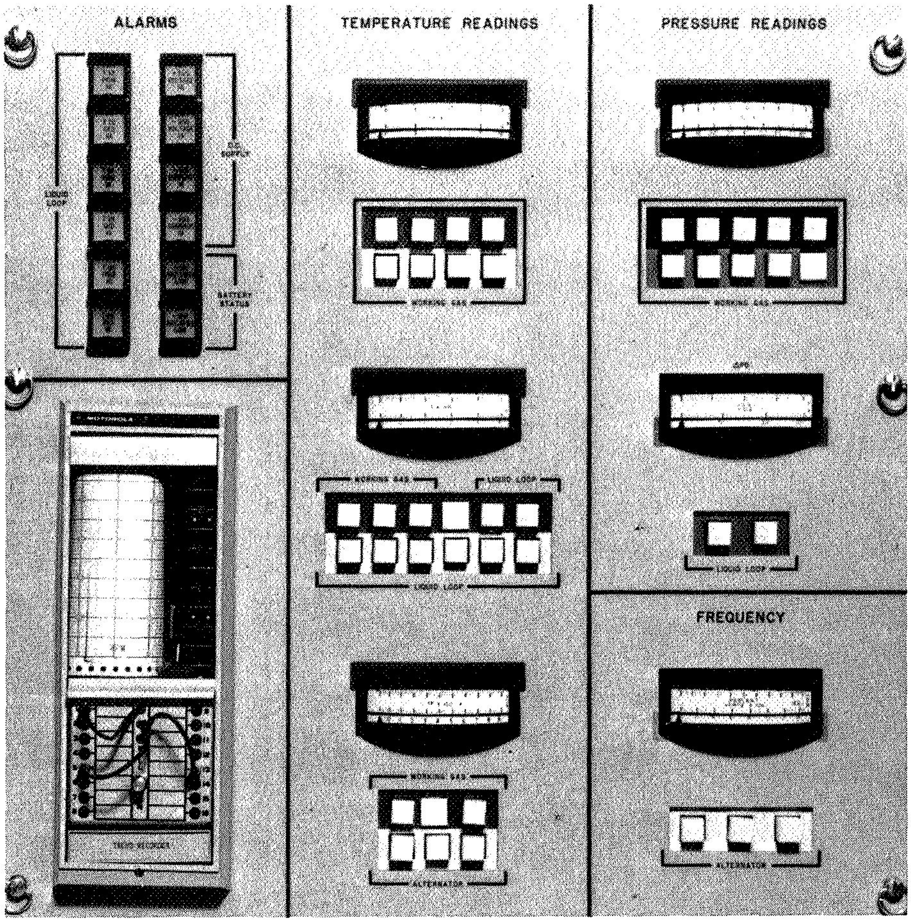


Figure 16. - Monitor panel.

E-5774

CONTROL SYSTEM PERFORMANCE

12 BPS STARTUPS AND SHUTDOWNS
2000 HOURS OF BPS OPERATION
PROTECTED BPS DURING OVERLOAD
OPERATED PRESSURE LEVEL CONTROL SEVERAL THOUSAND TIMES
TO MAINTAIN GAS LOOP PRESSURE
PROBLEMS WITH BRU SPEED SENSING CIRCUIT

Figure 17. - Control system performance during BPS testing.

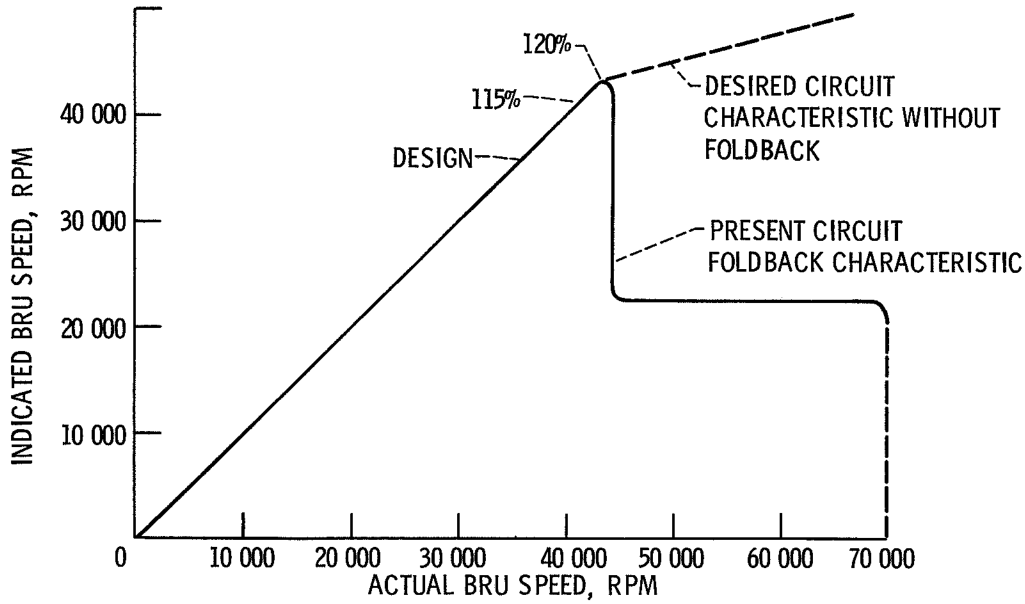


Figure 18. - Signal conditioner speed circuit characteristic.

NASA-Lewis